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Command and Staff College
Marine Corps University
2076 South Street
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Quantico, Virginia 22134-5068

MASTER OF MILITARY STUDIES

Title:

The Role of Diesel Engines in Early Submarine Development

Author:

LCDR Peter D. French, USN

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Mentor and Oral Defense Committee Member: Craig A Swanson, PhD

Approved: [Signature]

Date: April 26, 2010

Oral Defense Committee Member: Paul D French PhD

Approved: [Signature]

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Executive Summary

Title: The Role of Diesel Engines in Early Submarine Development

Author: LCDR Peter D. French, USN

Thesis: U.S. submarines could not have become an effective offensive weapon during World War II without the development of more advanced diesel engines due to the need for increased speed, range, endurance, and reliability.

Discussion: United States (U.S.) submarines played an important role in the Pacific during World War II, sinking over five million tons of Japanese shipping. This paper will show submarines could not have become an effective offensive weapon during World War II without the development of more advanced diesel engines due to the need for increased speed, range, endurance, and reliability. From the early days of submarines to advanced fleet boats of World War II, propulsion was a major factor affecting the use and tactics of submarines. The first submarines in the early 1900's were initially used as a coastal defense platform for breaking surface ship blockades and patrolling coastal waters. U.S. submarines began with dangerous gasoline engines and by 1915 moved to diesel power for safety and higher power output. A lack of reliability and the inability to provide the required speed or range plagued diesel development. The diesel engine was a key development in transforming submarines from defensive to offensive units, providing the submarine with the speed and range necessary to attack ships far from home port or supporting bases. When the war in the Pacific started, the newly developed diesel-electric drive submarines provided what skippers needed to confidently conduct wartime patrols. World War II submarines sank merchants and troop transports, an important task since Japan relied heavily on imports of raw materials to support its war effort.

Conclusion: To fight the war against Japan, the U.S. submarine force knew it needed submarines with the range, endurance, speed, and reliability to operate independently or with the fleet in the vast Pacific Ocean. The development of the high speed diesel with diesel-electric drive combined with the 1,200 ton fleet submarine resulted in fifty-five percent of all Japanese shipping losses. Submarines with advanced diesel engines were an important factor for World War II submarines success against Japan.

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Illustrations:

Figure 1. The 4-stroke diesel cycle. -----	7
Figure 2. The 2-stroke diesel cycle. -----	8
Figure 3. Diesel Direct Drive. -----	18
Figure 4. Diesel-Electric Drive. -----	19
Figure 5. Cross section of GM 16-278A engine. -----	20
Figure 6. Opposed piston principle. -----	21
Figure 7. Cross section of F-M 38D 8 1/8 engine. -----	23
Figure 8. Double-acting diesel principle. -----	25
Figure 9: Cross section of HOR 99DA engine. -----	26

Tables:

Table 1: M.A.N. vs BuEng Power Rating. ----- 16

Table 2: Weight Comparison of Direct Drive vs Diesel Electric Drive. ----- 17

Table 3: Early Submarine Diesel Engines. ----- 35

Table 4: High Speed Light Weight Diesels. ----- 36

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Table of Contents

Executive Summary -----	ii
Disclaimer -----	iii
List of Illustrations -----	iv
List of Tables -----	v
Acknowledgments -----	vi
Table of Contents -----	vii
<hr/>	
Introduction -----	1
Early Submarine Evolution until World War II -----	1-5
Development of pre-World War II Diesel Engines -----	5-17
High Speed Diesel Engines of World War II -----	17-28
Tactics, Technology, and Diesel Engines -----	28-31
Conclusion -----	31
End Notes -----	31-34
Appendix -----	35-36
Bibliography -----	37-38

United States (U.S.) submarines played an important role in the Pacific during World War II, sinking over five million tons of Japanese shipping. This paper will show submarines could not have become an effective offensive weapon during World War II without the development of more advanced diesel engines due to the need for increased speed, range, endurance, and reliability. From the early days of submarines to advanced fleet boats of World War II, propulsion was a major factor affecting the use and tactics of submarines. The first submarines in the early 1900's were initially used as a coastal defense platform for breaking surface ship blockades and patrolling coastal waters. U.S. submarines began with dangerous gasoline engines and by 1915 moved to diesel power for safety and higher power output. A lack of reliability and the inability to provide the required speed or range plagued diesel development. The diesel engine was a key development in transforming submarines from defensive to offensive units, providing the submarine with the speed and range necessary to attack ships far from home port or supporting bases. When the war in the Pacific started, the newly developed diesel-electric drive submarines provided what skippers needed to confidently conduct wartime patrols. World War II submarines sank merchants and troop transports, an important task since Japan relied heavily on imports of raw materials to support its war effort.

Submarines were initially conceived as coastal defense weapons. The Confederate Navy used the hand powered *Hunley* to sink the blockading *USS Housatonic* in 1864. While the *Housatonic* sank, so did the *Hunley*. The cost and risk associated with the submarine outweighed possible benefits and they were not used again in attempts to break the Union blockade.¹ Propulsion was one of the major failings of the early submarines. As new technologies developed, the battery and internal combustion engine, submarines became popular. The French envisioned using submarines to break blockades in 1886.² They employed their

battery powered submarine *Gustav Zede* in a successful mock attack against their battleship *Charles Martel* in the first successful demonstration of a submarine as a weapon in 1901.³ Other European countries quickly saw the importance of submarines as an effective weapon, but many still believed that more development was necessary to make these early submarines truly effective. Sir John Fisher, the First Sea Lord in 1904, believed the submarine needed greater endurance to be used as an offensive weapon.⁴ Endurance is the time a vessel can remain at sea as opposed to range, which is the distance a vessel can travel. Both increased range and endurance required larger submarines and countries struggled to build engines powerful enough to drive them. Germany, which would become the builder of the most advanced and powerful submarines by the end of World War I, did not believe submarines could be utilized as a truly practical weapon without better engines. After the development of the heavy oil engine, Germany jumped into the submarine business and quickly developed large overseas submarines.⁵ By 1913, Germany built U-Boats with Maschinenfabrik-Augsburg-Nurnberg A.G. (M.A.N.) diesels.⁶ The German diesel powered U-boats of pre-World War I had a speed of sixteen knots on the surface and a range of 7,800 miles.⁷ Unlike Germany, the U.S. had significant problems developing diesels that could provide the power, reliability, and power to weight ratio to complete the transition of submarines from a coastal platform to an overseas fleet boat.

The U.S., like several European countries, saw the submarine as a coastal defense weapon until World War I. After the French demonstrated the effectiveness of submarines in breaking a blockade, the U.S. began to develop submarines for the same purpose. The U.S. considered submarines an extension of the coastal artillery and used them as scouts.⁸ Submarines provided defense along the coast and protected vital shipping routes and ports. Submarine tactics prior to World War I called for the submarine to visually spot the target while

on the surface. After locating the target, the submarine approached and attacked the target while submerged at a range of 2,000 yards. This tactic placed a premium on underwater speed and battery endurance.⁹ In 1909, the General Board, the Navy's office responsible for ship development, tended to focus more on tactical mobility, the maximum surface speed used to put the submarine into firing position, than strategic mobility, the ability to transit to the place of action.¹⁰ The smaller submarines envisioned by the Board were still considered coastal submarines and lacked the range to stray far from home port, but maintained adequate surface speed to attack a target.

In 1910, officers of the Atlantic Torpedo Flotilla argued for a submarine with strategic mobility to attack enemy ships as they left their harbors.¹¹ By 1912, the Navy was beginning to see a use for fleet submarines. Transiting with the fleet, submarines could ambush enemy warships and cut off the enemy as they tried to break off their engagement.¹² As it became apparent that the diesel engines could not support the increasing speed of the U.S. fleet, the role of submarines changed. Submarines, placed in front of the battle fleets, would trap the enemy fleet between the submarines and the battle fleet.¹³ The development of the high frequency (HF) radio in 1916 allowed submarines to be used as forward scouts, operating with the fleet or independently. HF was capable of long ranges and allowed communications with boats anywhere in the Atlantic, and later, the Pacific. Entering World War I, the U.S. submarine force considered itself advanced and ready for war.

The submarines that entered World War I quickly learned some hard lessons. Until the S-class submarine first launched in 1918, submarines were considered harbor and coastal defense units. Only the K- and L-class boats saw action in World War I and the deficiencies of their small size quickly became apparent. The size of these coastal boats required they be towed to

England since they did not have range or reliability to cross the Atlantic by themselves. The ability of the submarine to quickly transit to the enemy location proved to be more important than high submerged speed. The current diesels lacked both speed and reliability. While U.S. submarines did not sink any U-boats, their attempts unnerved German U-boat captains. Submariners came out of World War I requiring bigger submarines that were better able to survive in the Atlantic and had better habitability and range.

While the U.S. submarines did not accomplish much during World War I, the experience showed the U.S. how far behind their submarine technology had fallen. The British and the Germans had faster, more reliable boats with better torpedoes and periscopes. Based on the success of the U-boat in World War I, the Navy saw the benefits of the submarine as an offensive weapon. The German U-boats claimed ten battleships, eighteen cruisers, twenty-one destroyers, nine submarines, and numerous merchants for a total of 5,708 Allied vessels with the loss of only 178 out of 373 U-boats.¹⁴ To counter the threat of the U-boat, the Allies had to expend a considerable amount of resources and develop new tactics such as convoys and anti-submarine warfare (ASW) planes.

During the interwar period, the Navy began looking to Japan as its next likely adversary. The Naval War College believed that, against Japan, submarines would be extremely effective in attacking merchants and troop transports in addition to forward scouting. Due to budget constraints and the Washington Naval Conference of 1922, the Navy lost its battlecruisers, making the submarine the primary unit for strategic scouting. The Washington Naval Conference also outlawed submarine blockades and the fortification of forward operating bases in the Pacific.¹⁵ The loss of the ability to sink merchants in warfare was a significant blow to submarine use, but they could still attack troop transports and other warships.

The build-up of the Imperial Japanese Navy in the early 1930's contributed to the United States' desire to build large fleet submarines capable of patrolling the Pacific.¹⁶ Larger submarines had the ability to stay on station longer in the vast Pacific without forward operating bases.¹⁷ Plan Orange, the strategy war plan for defeating the Japanese Navy, assumed that the Philippines would fall quickly to the Japanese, thereby eliminating any forward operating base. The large distances of the Pacific dictated a submarine would travel 8,000 miles from the West Coast to the Far East, which would take thirty-three days at ten knots. Patrols might last sixty to seventy-five days.¹⁸ Plan Orange also required submarines to travel at a fleet speed of seventeen knots. Without forward operating bases the S-class, developed for the Atlantic, could not operate in the Pacific due to the limited range and reliability issues. The S-class was ill suited for the Pacific, as it had no air conditioning or ventilation, limiting crew endurance. The S-class's small size created a limited range, solvable by filling ballast tanks with fuel which left behind oil slicks once submerged. Oil slicks made the submarines more susceptible to visual detection by surface ships and aircraft. The diesels were not powerful or reliable enough to keep up with the fleet transit speed of twelve knots.¹⁹

In 1933, during a conference with Submarine Officers, the plans for the *PORPOISE* class submarine were drawn up. The *PORPOISE* had diesel electric drive, eighteen knot surface speed, an endurance of seventy-five days, and a range of 11,000 nautical miles.²⁰ This design would form the basis for all future fleet submarines that were considered multipurpose and able to operate independently or with the fleet. U.S. submariners believed the fleet submarine would be a tremendously useful addition to the U.S. arsenal and an effective offensive weapon if used properly. To contribute to the war with Japan, the Navy needed submarines with speed, range,

and endurance. To provide the required speed and endurance the submarines needed to be larger and equipped with powerful, efficient, and reliable advanced diesel engines.

To become effective offensive weapons, submarines had to be capable of sailing at fleet speeds, be ocean going, and have the endurance to operate far from home port. These requirements necessitated large submarines with advanced diesel engines to power them. Power was a critical factor; to achieve increased range and endurance, the size of the submarine grew to accommodate larger fuel tanks and increased space for crew living. The requirement for speeds of up to twenty knots dictated the use of powerful diesel engines. These diesels were limited to certain revolutions per minute (RPM) by the propeller characteristics, and in size by hull characteristics for speed.²¹ Submarine speed was dependent on frictional resistance and wave making resistance. Frictional resistance was proportional to surface area and wave making resistance depended on the surface length ratio. The surface length ratio was speed divided by the square root of waterline length. The higher the surface length ratio, the more power the submarine required. Designers had to balance surface speed and submerged speed.²² To go faster on the surface, the hull had to be longer, which increased frictional resistance and slowed submerged speed, or the submarine had to be more powerful, resulting in longer and more complex power plants. A twenty knot surfaced submarine required 5,400 horse power (HP); to go twenty-two and a half knots, that same surfaced submarine required, 9,400 HP, almost twice the power. Designing diesels with such power proved unsuccessful due to torsional vibration, as demonstrated in the unsuccessful fleet sized T-class of the early 1920's.

On submarines, where weight affects the reserve buoyancy and there is little room for bulky engines, the power to weight ratio of diesels is extremely important. Two cycle engines have the advantage of a power stroke each revolution of the crankshaft as opposed to once every

two revolutions for four cycle engines. Two cycle engines typically had a better power to weight ratio than similar four cycle engines.²³ Two cycle engines, however, were less efficient than four cycles, both mechanically and thermally. Two cycle engines with shorter power strokes extracted less energy from the gas and the required mechanical accessories, such as the scavenger blower drive motor, decreased mechanical efficiency. The two cycle engines ran hotter without the cooling effect of the four cycle's intake stroke, requiring more robust cooling.

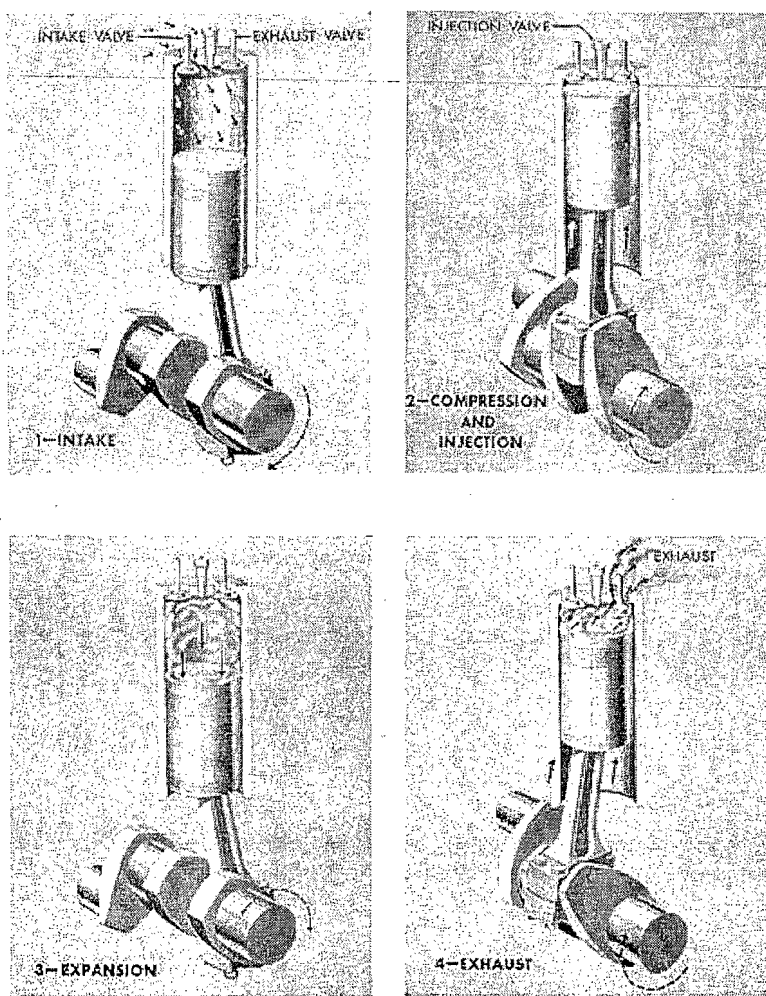


Figure 1. The 4-stroke diesel cycle.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946. <http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

The two cycle engine did have the important advantages of greater power to weight ratio, small and compact package, quieter and smoother power delivery, and reversibility, unlike the four cycle engines. Due to the limited space, submarine power plants were required to make power in a smaller package.²⁴ In comparison surface ship diesels in 1914 had a power to weight ratio of 350 lbs/HP compared to 50 lbs/HP for submarine diesels.²⁵

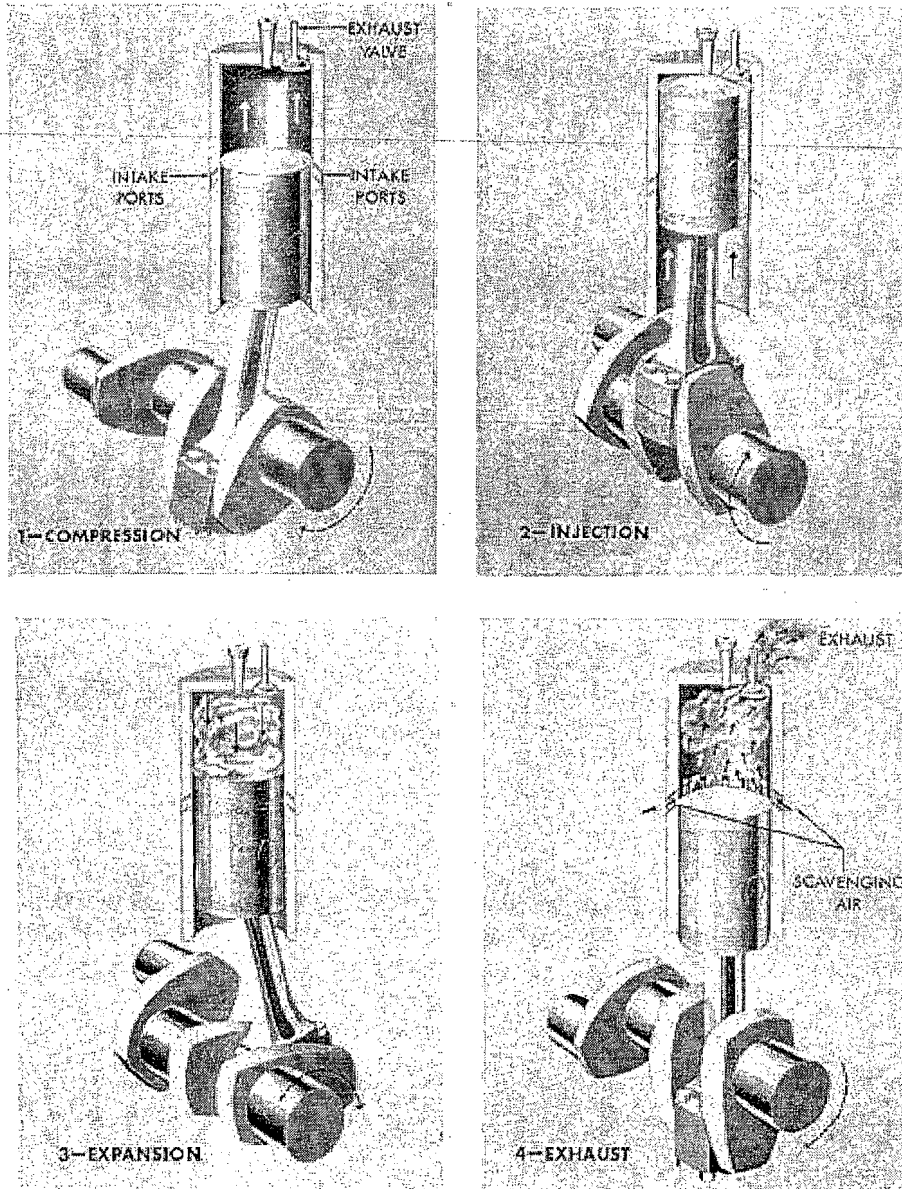


Figure 2. The 2-stroke diesel cycle.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946. <http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

Diesel engines needed to be reliable because critical failures of the engine on patrol made the difference between escape or destruction at the hands of enemy warships. The inability of submarines to carry spare parts and inadequate space to work on the engines limited the repairs that could be done at sea. Diesel engines that went into U.S. submarines missed the mark with underpowered, overweight, and unreliable engines until 1938 when General Motors-Winton (GM-W) and Fairbanks Morse (F-M) engines entered service.²⁶

The Navy did not start with diesel power in mind. The first design for a submarine was awarded to Holland's Torpedo Boat Company in 1895, and the submarine was to be steam powered.²⁷ Designers believed steam power would allow submarines to keep up with surface ships. Designers favored steam power because of its powerful and comparatively compact design, seen as the only practical way to increase submarine surface speed to twenty-five knots.²⁸ There were several things that made steam power impractical. Once submerged, temperatures could reach 160 degrees Fahrenheit and it took considerable time to surface and begin boiling water for propulsion. The weight of hot water tanks and associated machinery made the submarine heavy. Holland realized steam engines would never be successful and began looking at alternatives. Besides gasoline engines, Holland discussed the option of putting diesels into submarines with Colonel Edward Meier, the chief engineer of the Diesel Engine Company of America.²⁹ Colonel Meier had traveled to Germany to test Rudolph Diesel's original working prototype in September 1897.³⁰

The first U.S. Navy submarine, the *USS HOLLAND*, was commissioned in 1900 and powered by gasoline, since diesel engines were not yet advanced enough for submarines.³¹ Gasoline was not the ideal fuel for submarines. The volatile fuel tended to explode and the closed environment of a submarine made the fumes especially dangerous to the crew. In 1906,

after two disastrous explosions in gasoline powered submarines, the British Navy required the building of diesel submarines because the dangerous gasoline engines had reached their power limit.³² Gasoline engines were not as efficient as diesels because the gasoline mixture cannot get as hot or dense as diesel before it pre-ignites.³³ Gasoline engines cannot produce the same amount of power at the low RPM that marine diesels can achieve.

Rudolph Diesel developed his first working engine with twice the efficiency of conventional internal combustion engines in 1897.³⁴ The engine was not ready for marine use due to the complex injection system. By 1899, air blast injection or blast injection, which used highly compressed air to atomize the fuel to promote proper combustion, solved this problem.³⁵ The blast injection system added weight, additional complexity, and increased engine length due to the addition of the compressor. The system also leaked oil past the compressor piston rings, which then contacted hot air and tended to explode.³⁶ Preventative maintenance and increased reliability limited the potential for explosions. In 1909, Vickers developed the solid injection system which used fuel at an extremely high pressure, thereby eliminating the danger associated with blast injection. Solid injection created black smoke when improper amounts of fuel were used, something that gave away the stealthy submarine's position. Vickers' common rail injection system, developed in 1916, controlled the start and duration of the injection eliminating this problem.³⁷ Common rail or mechanical injection came into wide use by the early 1920's.³⁸ Early diesel engines, up to around 1910, had significant growing pains due to inadequate designs and a high degree of complexity, which required skilled operators. Several companies endured and continued to refine the engines, leading Rudolph Diesel to say in 1909, "With the help of the diesel motor it has become possible to attack and destroy hostile navies on the high seas before they can reach the neighborhood of the coasts and harbors."

The U.S. diesel industry started in 1898 with the Diesel Motor Company of America run by Adolphus Busch. The mismanagement and misuse of the patent rights secured from Rudolph Diesel put American diesel development behind by at least a decade.³⁹ The first diesel engines were four cylinder versions of a Vickers design that went into E- and F-class submarines.⁴⁰ Electric Boat Company (EBC) acquired licensing to build M.A.N. two stroke diesels in 1910.⁴¹ The EBC subsidiary, New London Shipbuilding and Engine Company (NELSECO) in Groton, Connecticut built these early engines that went into H- and K-class submarines in 1912. The engine, 75/6HS, rated at 450 HP @ 450 RPM, had mixed operational reviews after successful factory tests, which did not account for the shaft or how the engine was mounted once installed in the submarine, both of which affected vibration.⁴² The test also did not adequately model the loading and severe operating environment that the engine would be subjected to on the submarine. Once installed in submarines, the engines exhibited crankcase explosions, scored pistons and cylinders, broken wrist pins and air compressor valves. The Navy replaced all of the early NELSECO engines prior to World War I due to their questionable reliability.⁴³

To develop the skills necessary to build diesel engines the Navy sent Lieutenant Chester W. Nimitz along with other technicians to Germany to work with M.A.N. The experience did cost Nimitz a finger on his left hand, but also contributed to U.S. diesel technology for both surface vessels and submarines.⁴⁴ The second version of the NELSECO engine, used in the L-class after several improvements, also proved unreliable. The engines suffered from clogged sea water piping and leaking water pump glands that quickly filled the crankcase so it had to be drained. The layout of the engine did not allow for easy repacking of the pump, so the oil level in the crankcase had to be carefully watched to prevent the level from rising high enough to

damage the crankshaft.⁴⁵ These early engines were heavy compared to later engines and tended to fail due to deficiencies in American metallurgical technology.

NELSECO was unable to copy the M.A.N. two cycle diesels because the U.S. lagged behind the Germans in metallurgical technology. NELSECO had the German plans and assistance from German engineers, but the foundries could not duplicate the casting to German specifications. It was later discovered that the Germans only allowed the export of two cycle technology that they were unable to perfect. The Germans used 850 HP and 1000 HP four cycle engines in their World War I U-boats.⁴⁶ The Americans, slow to take advantage of advances in metallurgical technology, could not match the superior technology in casting processes, alloy development, and heat treatments that the Germans and other European countries possessed. The U.S. commercial foundries did not want to undertake the risky development casting of low volume pieces, so the Navy Yards cast most of the complex pieces for the diesels.⁴⁷ As a result, ninety percent of cylinders cast for the first NELSECO engines were rejected.⁴⁸ The resulting U.S. engines in submarines tended to be heavier and more susceptible to failure than the German design on which they were based, because the Germans could cast lighter, stronger, and more complex assemblies for their engines. This disadvantage in engine technology continued until the U.S. stopped copying the Germans and used their own designs in the mid-1930's.

After the unfavorable results with the 75/6HS, NELSECO developed a four cycle design based on G.C. Davidson's commercial engine in 1912. The 6-EB-14, a six cylinder, 440 HP @ 400 RPM engine, began replacing the M.A.N.-based two cycle and went into R- and O-class submarines.⁴⁹ The engine had a better record than the 75/6HS and was even sold to several foreign navies including Britain and Spain.⁵⁰ The success of the "rock crusher," as the engine was known in the fleet, combined with the poor performance of past two cycle designs, biased

the U.S. towards four cycles until the development of the high speed diesel in the 1930's.⁵¹ The R- and O-class remained coastal submarines because they only displaced 500 tons and were too small for true open ocean operation. The 6-EB-14, despite its reliability, did not have the power to propel a larger fleet submarine at the design speed of twenty knots. The request came from the Navy in 1916 for a fleet submarine capable of twenty knots powered by 1,000 HP diesels.⁵²

The T-class submarines, designed to be large fleet types with the ability to patrol at long ranges, never achieved their design speed of twenty knots. T-class submarines were obsolete by the time they were commissioned in 1920, since the fastest battleships could transit at twenty five knots.⁵³ The T-class used four larger versions of NELSECO's proven six cylinder design. Two engines, connected to a single shaft, resulted in a powertrain 100 feet long. The unreliable T-class engines suffered from failures of two stage injection air compressors and the heat related failure of pistons, cylinders, and cylinder head. A weak, flexible bed plate resulted in prevalent axial alignment problems in the long powertrain. The engines also suffered from severe vibration issues that led to crankshaft failure.⁵⁴ The large engines brought to light a problem that plagued virtually all large diesel engines of U.S. manufacture: torsional vibration. Vibration was a problem not a considered during the design of the T-class submarines and went unsolved until the V-class submarines of the late 1920's.

The Navy believed an 800 ton intermediate boat similar to ocean-going German U-boats of World War I would be sufficient for Atlantic operations.⁵⁵ The Navy ordered fifty-two of the S-class submarines, the majority of which were powered by NELSECO 8-EB-15 600 HP @ 380 RPM engines. NELSECO engines were not fully developed, but EBC built the submarines anyway. The submarines initially authorized in 1916 had so many problems the first was not delivered until the war was over in 1918.⁵⁶ The engines had severe vibration issues due to the

critical speed that occurred a few RPM below the maximum rated power. The submarine never reached its top speed because it was limited in RPM to prevent failures. *S-1* suffered from broken crankshafts, broken crankcase tie bolts, stripped camshaft drive gears, and stripped jacking gear keys. These were serious failures which required significant time and effort to repair in port. The Navy determined that NELSECO did not increase the diameter of the crankshaft journals as was necessary when they increased the size and power of the engine. As a quick and inexpensive fix, the RPM was lowered while the horsepower output remained constant.⁵⁷ In addition to bearing failure, the increased loading on the engine resulted in cracked heads and exhaust valve seats. The Navy eventually increased the journal diameter which reduced the vibration related failures and allowed for the increase of engine output to its original specification of 600 HP @ 380 RPM.⁵⁸ NELSECO was not the only engine supplier to the Navy, but after the fiasco with the S-class there were no more commercially developed diesels until the mid-1930's.⁵⁹

U.S. designers had to overcome the problem of torsional vibration to develop the power and reliability needed for an effective offensive fleet submarine. The twisting of the crankshaft during the power stroke creates torsional vibration and, as the engine reaches critical speed, the vibrations reinforce themselves, causing destructive forces that quickly destroy the engine.⁶⁰ The designers assumed the shaft that connected the diesels to the propellers was rigid enough so that the absorption of vibrations could be ignored during the design process. The shaft absorbed the engines harmonic torsional vibration and acted as a spring, magnifying the vibrations and then sending them back into the engine. Often the crankshaft was too weak to handle these vibrations and failed.⁶¹ The destructive critical speed typically occurred within the normal operating range of submarine engines.⁶² Critical speeds were first calculated in 1919 but the U.S. and other

navies managed to work around them by building heavier, stronger diesel engine casings or not running at critical speeds.⁶³ The vibration problem could not be truly eliminated until the development of diesel-electric propulsion in the 1930's, but the problems were minimized with stronger crankshafts, elastic couplings, different flywheels, and derating engines to keep them from operating at critical speed.

The Navy had an excellent source of engine and submarine technology in the German U-boat. Several officers within the submarine community believed the U.S. should take advantage of the technologically superior captured U-boats. The Navy, however, believed that if the Germans could build reliable submarines, the U.S. could as well and without copying them. The Navy even declined plans and engineering services from Germaniawerft, Germany's leading U-boat manufacturer.⁶⁴ U-boats could maneuver right up to the pier on diesel power, something U.S. boats could not do because of the complex reversing mechanisms in diesels which meant most skippers used electric power for astern propulsion.⁶⁵ The Germans had better clutches that could be rapidly disengaged and did not bind. The significant time required for U.S. diesels to stop and disengage the shaft made rapid diving, important for submarines on wartime patrols, dangerous. Submarines had to submerge rapidly to avoid enemy aircraft and propulsion was needed quickly to maintain depth. The ability to crash dive was not as important during World War I, but the U.S. realized it would become a vital skill to avoid Japanese aircraft in the Pacific. The *USS JACK (SS-259)*, a fleet boat commissioned in 1943, trained to a wartime crash dive standard of thirty seconds, a time measured in minutes on S-class boats in the 1920's⁶⁶ The U-boats also had superior engines. One captured U-boat, compared directly against the *S-3*, turned out to be three knots faster.⁶⁷ The captured U-boats were so reliable and easy to operate that, when they cruised from Germany to the West Coast with unskilled mechanics, they suffered no

failures. In one U-boat engine disassembled after 25,000 miles of service, the machining marks were still visible on the internals of the oil pump, which frequently failed on S-class submarines.⁶⁸ The Navy could clearly benefit from the technologically superior engines in the U-boats even if they did not copy other aspects of the submarine.

The Navy needed a reliable diesel engine source and since U.S. domestic manufactures could not produce a reliable design or copy, the Navy Bureau of Engineering began to design their own. The Bureau began building copies of the M.A.N. engines in captured U-boats, but the U.S. lagged so far behind in metallurgical technology that the New York Naval Yard (NYNY) could only build detuned engines weighing ten percent more than the copied engines.⁶⁹ Beginning in 1919, Bureau-M.A.N. engines rated at 1000 HP @ 425 RPM, heavier copies of M.A.N. six cylinder S 6 V 45/42 1200 HP @ 450 RPM diesels, replaced NELSECO engines in S and V-class submarines.⁷⁰ By 1930, the Bureau of Engineering, confident in its engines, rated them at their designed power, comparable to what the Germans used thirteen years earlier.⁷¹

BHP Rating		Cylinders	Bore x Stroke (in)	RPM	
German	BuEng			German	BuEng
3,000	2,350	10	20 $\frac{1}{2}$ x 20 $\frac{1}{2}$	380-390	345
1,750	1,400	6	20 $\frac{1}{2}$ x 20 $\frac{1}{2}$	380-390	345
1,200	1,000	6	17 $\frac{1}{2}$ x 16 $\frac{1}{2}$	450	425
550	550	6	13 $\frac{1}{2}$ x 13 $\frac{1}{2}$	450	—
450	450	6	13 $\frac{1}{2}$ x 13 $\frac{1}{2}$	—	425

Table 1: M.A.N. vs BuEng Power Rating

Source: Cummins, Lyle. *Diesels for the First Stealth Weapon-Submarine Power 1902-1945*. Wilsonville, OR: Carnot Press, 2007.

The U.S. now had a reliable diesel, but they failed to create enough power to propel fleet type submarines. The Bureau-M.A.N. engines, outdated and heavy, consumed a disproportionate

amount of space on board submarines. In 1931, Edward Magdeburger, the Bureau's chief diesel expert, realized that the Navy needed smaller, more powerful diesels.⁷² The Navy then designed an engine based on the light weight M.A.N. M 9 V 40/46 for use in the large V-class submarines. As with previous efforts to build a larger and more powerful engine this one resulted in disaster. The 1535 HP @ 450 RPM engine suffered from severe vibration issues.⁷³

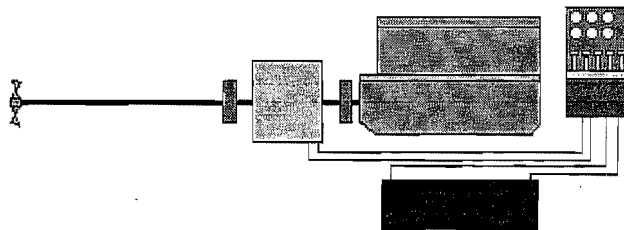
In 1932, the Navy sponsored a competition to build a smaller, higher RPM diesel for land or sea.⁷⁴ The competition sponsored by Captain Samuel Robinson had two goals: develop high speed diesel for diesel electric drive, and increase submarine surface speed from seventeen to twenty-one knots.⁷⁵ The only criterion to be met by designers was the engine must weigh less than twenty-seven and a half pounds per horse power.⁷⁶ The Navy hoped to attract suppliers from the locomotive diesel industry, thereby creating a larger market and presumably a better product. The powerful and reliable diesel the Navy had been seeking to transform the submarine into a formidable offensive weapon emerged from the competition.

	Engines	Surface Tons	Speed Knots	Main Eng.s.& Motors, lbs.	Vol. Eng. Aux.& Motor rms., cu. ft.
Bureau-M.A.N. (V-5 Narwhal)	2 - 2,350 hp w/ 2 - 450 hp aux	2,730	17.44	477,000	30,900
Bureau-M.A.N. (V-7 Dolphin)	2 - 1,750 hp w/ 2 - 450 hp aux	1,540	17.31	316,590	17,072
M.A.N. M9V (V-8 Cachalot)	2 - 1,535 hp No aux engs.	1,130	17 est.	177,129	8,860
Admiral Robinson's forthcoming new generation diesel-electric drive boats compare very favorably with the above three with direct drive engines:					
Winton-GM (SS 172 Porpoise)	4 - 1,300 hp w/ 3 - 150 hp aux	1,292	18.8	232,808	10,850

Table 2: Weight Comparison of Direct Drive vs Diesel Electric Drive.

Source: Cummins, Lyle. *Diesels for the First Stealth Weapon-Submarine Power 1902-1945*. Wilsonville, OR: Carnot Press, 2007.

By 1935, Admiral Samuel Robinson firmly believed the shortcomings of direct drive diesel propulsion could only be overcome by smaller diesels operating at a higher RPM. This resulted in diesel electric propulsion where the diesels were connected to a generator which turned an electric motor connected to the shaft.⁷⁷ The U.S. chose to rely exclusively on the success of unproven diesel electric drive and was the only navy to use diesel electric drive until after World War II. Diesel electric drive had many advantages. Torsional vibration could be minimized by separating the long diesel engine from the shaft and running multiple smaller engines which suffered less from torsional vibration to power electric motors. Although diesel-electric drive weighed more than direct drive, the elimination of critical speeds and the flexibility of being able to run multiple engine combinations outweighed this disadvantage. The engines ran at optimum efficient speed and shutting one engine down for repairs did not result in a significant loss of speed.⁷⁸ The first company to provide an engine for use in diesel electric drive was GM-W.

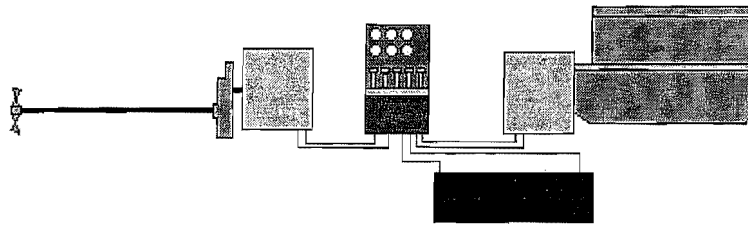


DIRECT DRIVE:

In this direct-drive power system, the diesel engine is directly connected to the propeller shaft. Between the engine and the propeller shaft, there is a large, combination electric motor/generator. A clutch connects the engine to the motor/generator. A second clutch connects the motor/generator to the propeller shaft.

Figure 3. Diesel Direct Drive.

Source: Fleetsubmarine.com, <http://www.fleetsubmarine.com/propulsion.html>



DIESEL-ELECTRIC DRIVE:

The solution was to use full-time electric drive for the propeller shafts. Adapting a system originally developed for trains, the diesels were directly coupled to a large direct current generator. This power could then be used for charging the batteries, or powering the motors. Since there were four engines and generators, it was possible to use the full power output for the motors, charging the batteries, or a combination of the two.

Figure 4. Diesel Direct Drive.

Source: Fleetsubmarine.com, <http://www.fleetsubmarine.com/propulsion.html>

GM-W, a division of General Motors run by Charles Kettering, built locomotives and rail cars. GM-W diesels in locomotives transformed the rail industry in 1934, setting several speed records.⁷⁹ The development work that went into these diesels paid dividends when applied to submarine diesels. The GM-W 16-201A developed 1300 HP @ 750 RPM and included advances such as unit injection, roots type blowers for scavenging air, and a stronger welded block.⁸⁰ The 16-201A had initial problems like most other diesels such as cracked heads and pistons, but the larger 16-248A addressed all these problems. The 16-248A had a stronger crank case, better pistons, and piston rings.⁸¹ The 16-248A, rated at 1600 HP @ 750 RPM, unfortunately was not robust enough to operate in severe submarine conditions at maximum power output.⁸² Designers increased the size and developed the 16-278A which maintained the same rating, but could now handle the stress of running at maximum output.⁸³ Between 1938 and 1944, fifty-two submarines received the 16-248A and seventy-four were commissioned with

the 16-278A.⁸⁴ The GM-W's were the first of two successful diesels used in World War II submarines.

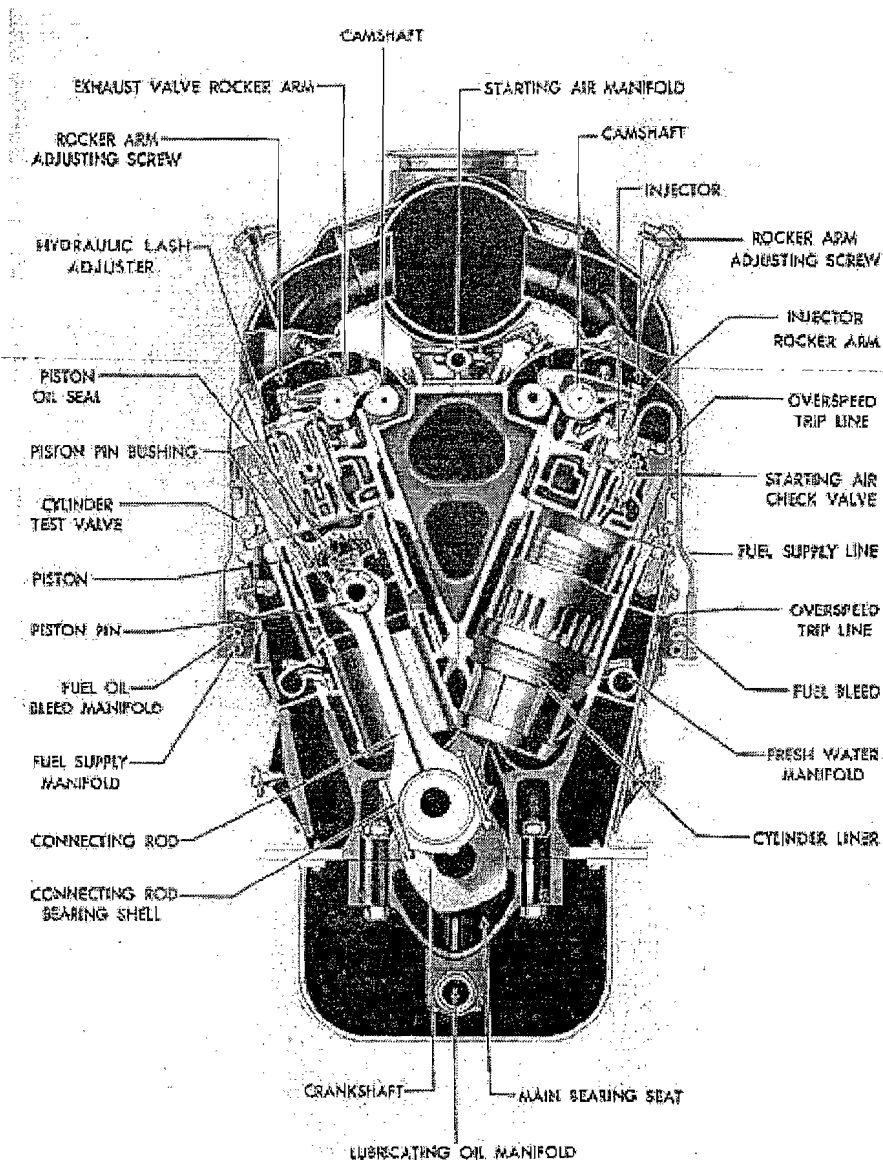


Figure 5. Cross section of GM 16-278A engine.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946. <http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

F-M submitted designs in the second year of the high speed diesel competition for use on sea or land. The company was awarded a contract in 1934.⁸⁵ The initial eight cylinder version 38A8 developed 1300 HP @ 720 RPM but suffered from cracked cylinder blocks. After

redesigning the block and using stress relieving techniques and magna fluxing, a procedure used to detect cracks, nine and ten cylinder versions were designed for submarines. Both versions were rated at 1600 HP @ 720 RPM.⁸⁶ The F-M design differed significantly from the GM-W designs and had several advantages.

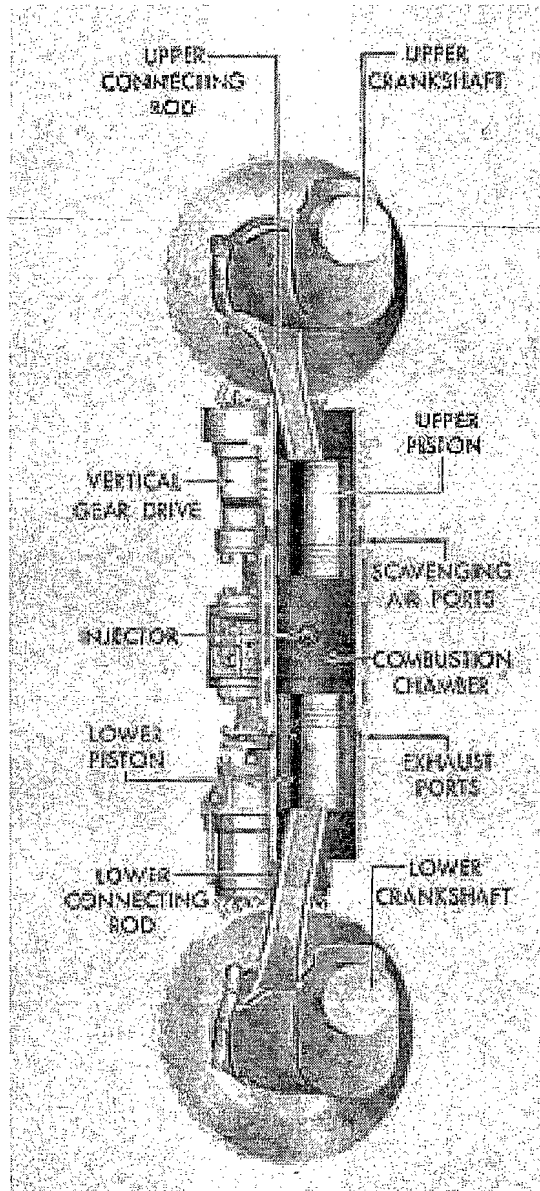


Figure 6. Opposed piston principle.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946.
<http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

The use of F-M engines alleviated the Navy's concern that GM-W would have a monopoly on submarine engines. The F-M was an opposed piston design developed under license from the German Junkers Company based on Jumo engines used in long range flying boats in 1930. The opposed piston design produced more power in a compact, lighter package than conventional designs.⁸⁷ Vertically opposed pistons drove two crankshafts coupled by gears. The upper crankshaft drove a scavenging blower with the lower crankshaft driving geared accessories such as oil and coolant pumps. Without a cylinder head, there were no failures of cylinder head gaskets or cracked heads. The lack of cylinder heads also resulted in higher thermal efficiency. The engines could be brought to maximum power more quickly and cooled faster than more conventional diesel engines. From a maintenance stand point, the F-M engines ran for longer periods, approximately 4,000 hours compared to 2,500 hours for GM-W engines, but maintenance took longer and was more difficult due to the second crankshaft.⁸⁸ The cumbersome maintenance process prevented the F-M from selling well in the civilian locomotive industry.⁸⁹ Despite its lack of success in the civilian market, it was very successful in submarines. 480 submarines were powered by F-M engines and they are still used in today's nuclear powered submarines for emergency power.⁹⁰

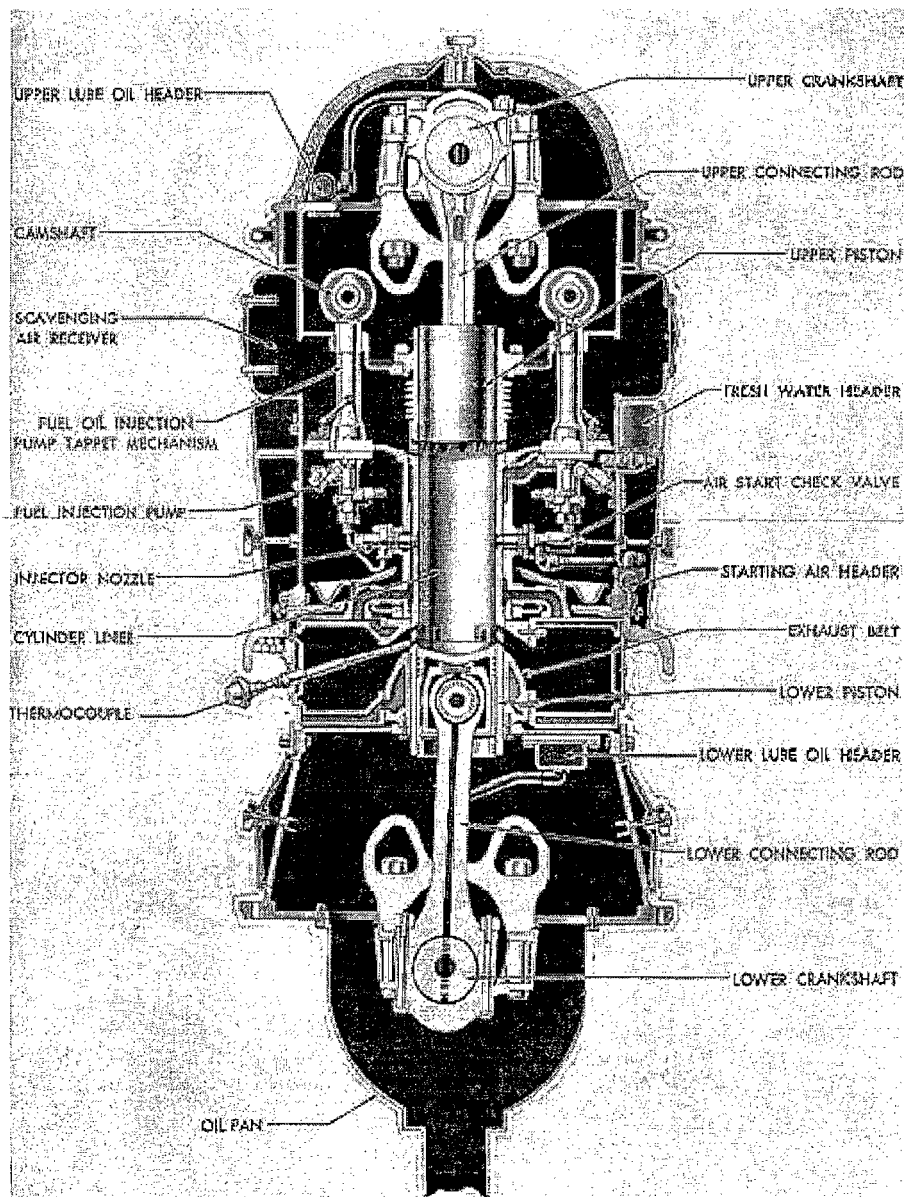


Figure 7. Cross section of F-M 38D 8 1/8 engine.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946. <http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

The Navy decided to use a third manufacturer with disastrous results. Hooven, Owen, and Rentschler (HOR) received a Navy contract in 1934 to provide engines for twenty submarines.⁹¹ HOR secured licensing from M.A.N., after NELSCO failed to impress M.A.N. engineers, to develop a version of the M8Z 23/34, a double acting design.⁹² HOR had

impressive foundry experience, important because metallurgy was a weakness for many engine builders, and extensive experience in building marine and stationary diesels.⁹³ The HOR engine, chosen for its compact, powerful design, was meant to supplement GM-W and F-M in order to ensure adequate engine availability for wartime submarines.⁹⁴ On paper the HOR 89DA, 1300HP@700RPM and 99DA, 1535HP@700RPM compared favorably with the F-M and GM-W engines. The double acting design created power on each stroke and the engine was twelve percent lighter than the GM-W engines. In practice, however, the complex design made the engine prone to failure and had a detrimental effect on combat operations.

Despite wide success in the surface fleet where 600 engines were in use powering small ASW ships, the ill fated HOR engines failed in submarines.⁹⁵ The dual acting design required two cylinder heads with the connecting rod going through one of them. The piston, subjected to combustion on both sides, required a complex cooling system. The packing gland for the connecting rod was subject to high temperature and pressure which resulted in frequent failure. The lower head suffered frequent cracking and bolt failure.⁹⁶ The engines, far noisier than other two cycle diesels, used forty percent more air than F-M and GM-W engines.⁹⁷ Poor quality control resulted in improper heat treatment of blower drive gears that caused catastrophic failure.⁹⁸

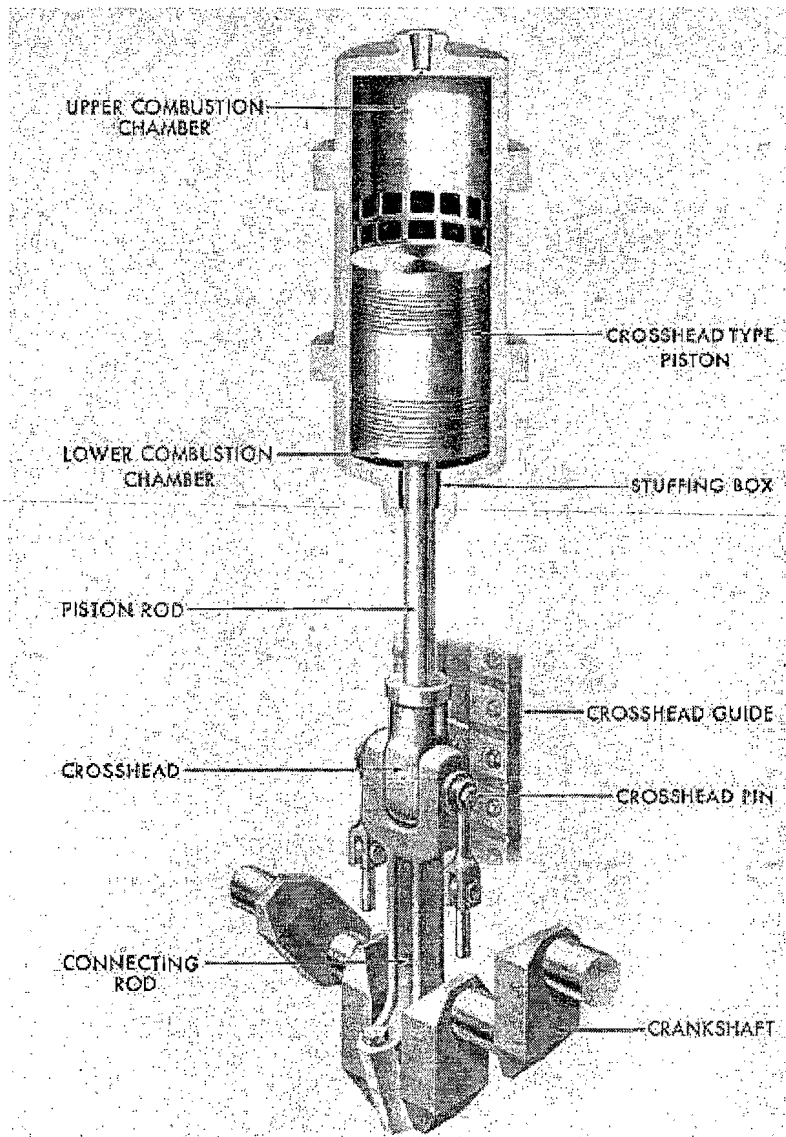


Figure 8. Double-acting diesel principle.

Source: Commander Submarine Forces Atlantic. *Submarine Main Propulsion Diesels*. NAVPERS 16161 Washington, DC: Standards and Curriculum Division Training, Bureau of Naval Personnel, 1946. <http://www.maritime.org/fleetsub/index.htm> (accessed December 15, 2009).

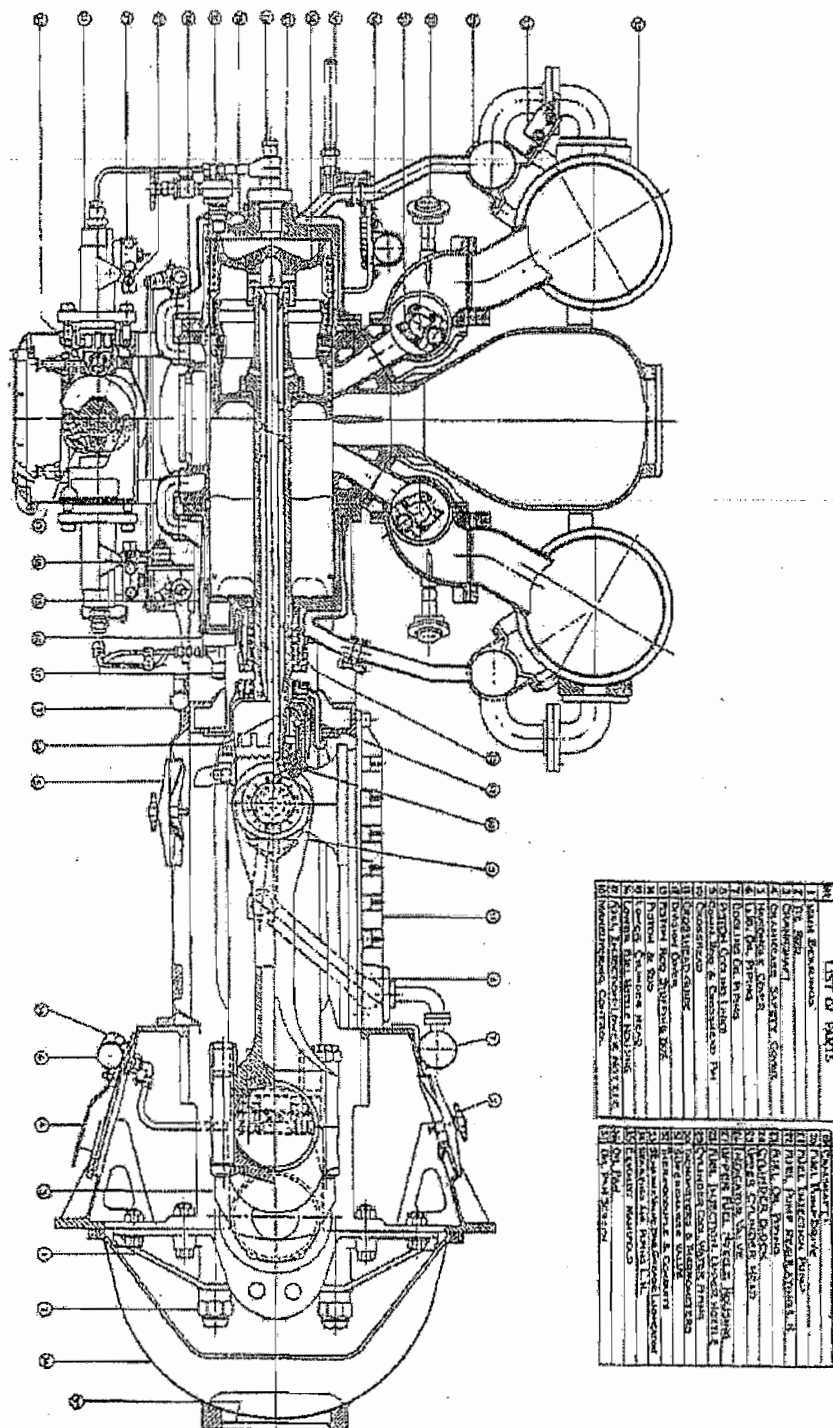


Figure 9: Cross section of HOR 99DA engine.

Source: Cummins, Lyle. *Diesels for the First Stealth Weapon-Submarine Power 1902-1945*. Wilsonville, OR: Carnot Press, 2007.

USS GUNNEL (SS-253) suffered failure of all four of its HOR engines while crossing the Atlantic. Stranded 1,000 miles from her base the *GUNNEL* limped into port on her auxiliary diesel at two knots.⁹⁹ On the *USS POMPANO (SS-181)*, engines were destroyed before the boat left the building yard at Mare Island, California. It took nine months to correct the problems enough for the *POMPANO* to get underway.¹⁰⁰ The problems with the HOR engine were brought to the public's attention in 1939. The *New York Times* published an article detailing the Navy's problems with the HOR and suggested that they may have been due to intentionally faulty designs sold by the Germans.¹⁰¹ The *USS JACK (SS-259)* was one of twenty submarines that ran HOR engines during World War II. The *JACK* was powered by four HOR engines during her first two patrols in the Pacific during World War II. Even before leaving the East Coast the engines experienced problems and their transit to the West Coast was delayed for five months while new spring loaded timing gears were installed on all engines.¹⁰² Once the *JACK* reached the West Coast, rings had to be replaced due to excessive oil consumption.¹⁰³ After her first patrol, the timing gears were again replaced and on her second patrol the crankshaft broke in the number two engine.¹⁰⁴ The repeated failures and questionable reliability had a tremendous impact on the crew and the submarines ability to use speed during an attack.

World War II submarines used their surface speed of twenty knots to great advantage over the slower Japanese ASW and merchant ships. The loss of one engine reduced the submarines' speed to fifteen knots, eliminating the speed advantage over the ASW ships.¹⁰⁵ During a surface attack, the loss of one engine could be the difference between getting away cleanly and losing the submarine. After the *JACK's* second patrol, in October 1943, she returned to Mare Island Naval Ship Yard for upgrades to GM-W 16A-278's; two HOR engines failed during the transit.¹⁰⁶ The new GM-W's brought confidence to the crew and allowed them to

successfully engage convoys, often engaging the same convoy multiple times. Several wartime reports contained negative comments about HOR engines and the detrimental effect their lack of reliability had on wartime patrols.¹⁰⁷ “The HOR engines saved the Japanese thirty to forty ships,” said Thomas Dykers, Commanding Officer of the *JACK*.¹⁰⁸ The HOR engines left their mark on the submarine force and marked the pinnacle of failure in the Navy’s long battle to find a successful diesel engine. With more development time the HOR could have become a reliable engine but the onset of war and poor performance caused their replacement in all submarines originally equipped with HOR engines.

The development of high speed, light weight diesels, diesel-electric drive, and radar influenced the tactics used during World War II. Prior to the war, the Navy had perfected sonar originally used during World War I. Submarine tactics called for a submerged approach, firing a salvo of three torpedoes per target. The submarine would transit at twenty knots, now possible due to the advanced diesels, to position in front of the convoy and submerge. The submerged attack would be done from the preferred firing position off the beam of the target ship. Two targets were selected and two salvos of three torpedoes were fired at a range of 1,500-2,500 yards.¹⁰⁹ The prewar doctrine stated attacks could be made using sonar bearings alone, but actual war practice tended to be at periscope depth using visual bearings for increased accuracy.¹¹⁰ The speed provided by the diesel engines allowed submariners develop different and more effective tactics, such as night time surface attacks.

Submarines first received surface search radar in 1942, which combined with high surface speeds, made for very effective night time surface attacks. *USS HARDER (SS-257)* was the first U.S. submarine to conduct a night time surface attack using the SJ surface search radar in August 1942.¹¹¹ Submarines were faster, more maneuverable, and difficult to see on the

surface at night. The high speeds allowed a single submarine to attack the same convoy multiple times, leading the Japanese to believe that the U.S. were using wolf pack tactics similar to the Germans. The Germans had previously used night time surface attacks to great effect until Allied shipping was fitted with radar.¹¹² Fortunately the Japanese had no or very ineffective radar to counter night time surface attacks. Night time surface attacks accounted for thirty percent of attacks in 1942 and fifty-seven percent by 1944.¹¹³ Speed and radar were used in combination with the submarine's deck gun to destroy small ASW craft or merchants that did not rate a torpedo.¹¹⁴ Diesel engines had a marked effect on tactics and made submarines very effective offensive weapons during World War II.

The submarine played a significant part in the defeat of Japan. Prior to entering the war the Navy believed that unrestricted submarine warfare would not be conducted since it was banned by international law. Unrestricted warfare was one of the major lessons learned by the Germans in World War I and it went largely ignored by the U.S. Navy during the interwar period. Due to this institutional belief, the Navy did not practice attacks on merchants or surface attacks at night until the start of World War II.¹¹⁵ Both Britain and Germany started unrestricted submarine warfare in 1939; the U.S. followed suit once entering war against Japan.¹¹⁶ Japan's merchant fleet was already stretched thin at the beginning of the war and the capture of distant islands only made the situation worse. U.S. submarines began exacting their toll on the Japanese merchant fleet, and the Japanese had no program to quickly replace losses, similar to the Allies in their struggle against Germany.¹¹⁷ The U.S. submarine force slowly strangled the Japanese through commerce raiding.

The U.S. submarines were initially hampered by seriously defective torpedoes during the first two years of the war. Defective components included magnetic exploder, depth control

mechanism, and contact exploder.¹¹⁸ In one such case, the *USS TUNNY* (SS-282), operating off Hong Kong, spotted a lone tanker on the surface in February 1943. After firing six torpedoes which suffered various casualties, the seventh, which was running erratically, scored a lucky hit as the tanker turned into the torpedo during her evasion.¹¹⁹ With better torpedoes from the start, U.S. submarines would have significantly impacted Japanese shipping much earlier in the war. U.S. submarines attacked one third of the merchants sighted and sent 5.3 million tons to the bottom. Submarine attacks resulted in over fifty percent of Japanese shipping losses.¹²⁰ Submarines also added one battleship, eight carriers, and eleven cruisers to their total.¹²¹

One of the most effective weapons used in conjunction with submarine speed and range was that of the ability of U.S. code breakers. The Ultra program allowed the U.S. to read and listen to coded Japanese transmissions. Since the Japanese often sent messages detailing the location, direction, and speed of convoys, submarines used their high surface speeds to intercept and engage many of the convoys.¹²² The range and endurance allowed the submarines to wait in Japanese waters for extended periods for enemy ships. Without high speed diesels, U.S. submarines would have lost many opportunities that Ultra provided since submarines were one of the few units that could make use of this information on targets in enemy waters.

Submarines effectively located and sunk enemy warships. Submarines got into position to sink convoys that held enemy reinforcements for Guam and several other critical areas during the war. *USS CAVALLA* (SS-244) and several other submarines provided scouting reports to Admiral Spruance of enemy fleet movements during the invasion of Saipan.¹²³ U.S. Submarines stationed off Tawi Tawi in the Philippines waited for the Japanese fleet to sail. On June 13th, 1944 the *USS REDFIN* (SS-272) spotted the fleet as it sailed for the Marianas.¹²⁴ *USS ALBACORE* (SS-218) and *CAVALLA* were able to sink two Japanese carriers, *Shokaku* and *Taiho*,

during the great Marianas Turkey Shoot.¹²⁵ The confusion caused by the two submarines made the Japanese fleet easier targets for the U.S. aircraft.¹²⁶ Submarines had the range and speed necessary for them to conduct effective missions against Japan including commerce raiding, anti-surface warfare, scouting, combat search and rescue, and intelligence gathering.

U.S. submarines overcame a difficult development from coastal defense weapons to effective offensive weapons that delivered a crippling blow to the Japanese in World War II. To fight the war against Japan, the U.S. submarine force knew it needed submarines with the range, endurance, speed, and reliability to operate independently or with the fleet in the vast Pacific Ocean. The development of the high speed diesel with diesel-electric drive combined with the 1,200 ton fleet submarine resulted in fifty-five percent of all Japanese shipping losses. The fleet submarine was able to use its speed during surface attacks, outpacing slower convoys and ASW ships. It could quickly travel long distances to intercept enemy warships. The power of the diesel engines allowed for the size necessary to carry fuel and supplies for long endurance and range. The range and endurance of the fleet boats allowed them to operate from bases far from Japan and spend a significant amount of time in enemy waters sinking ships and collecting intelligence. The resulting reliability of the high speed diesels allowed the submarines to attack with confidence knowing the engines would not fail at a critical time. The submarines could venture far from their support base knowing the reliable engines would bring them home again. Submarine diesels with speed, reliability, endurance, and range were an important driving factor for World War II submarine success against Japan.

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⁴⁶ Norman Friedman (*Through 1945*), 358.
⁴⁷ Edward C. Magdeburger, 70.
⁴⁸ Lyle Cummins, 219.
⁴⁹ Lyle Cummins, 224.
⁵⁰ Lyle Cummins, 224.
⁵¹ Edward C. Magdeburger, 64-65.
⁵² Clay Blair Jr., 20.
⁵³ Lyle Cummins, 321.
⁵⁴ Lyle Cummins, 319.
⁵⁵ Norman Friedman (*Through 1945*), 151.
⁵⁶ Edward C. Magdeburger, 66-68.
⁵⁷ Lyle Cummins, 340.
⁵⁸ Lyle Cummins, 341.
⁵⁹ Lyle Cummins, 347.
⁶⁰ Norman Friedman (*Through 1945*), 256.
⁶¹ Lyle Cummins, 664.
⁶² John D. Alden (Article), 43.
⁶³ Norman Friedman (*Through 1945*), 359.
⁶⁴ Lyle Cummins, 347.
⁶⁵ Lyle Cummins, 260.
⁶⁶ Lyle Cummins, 341 and James F. Calvert, 6.
⁶⁷ Lyle Cummins, 261.
⁶⁸ Lyle Cummins, 259.
⁶⁹ Lyle Cummins, 348.
⁷⁰ Lyle Cummins, 350.
⁷¹ Lyle Cummins, 354.
⁷² Lyle Cummins, 663.
⁷³ Lyle Cummins, 664.
⁷⁴ John D. Alden (Article), 43.
⁷⁵ John D. Alden (Article), 44.
⁷⁶ Edward C. Magdeburger, 75.
⁷⁷ Lyle Cummins, 663.
⁷⁸ Norman Friedman (*Through 1945*), 259.
⁷⁹ Lyle Cummins, 672.
⁸⁰ Lyle Cummins, 672.
⁸¹ John D. Alden (Article), 48.
⁸² Lyle Cummins, 679.
⁸³ Lyle Cummins, 690.
⁸⁴ Lyle Cummins, 697.
⁸⁵ Lyle Cummins, 710.
⁸⁶ Lyle Cummins, 711.
⁸⁷ John D. Alden (Article), 46.
⁸⁸ Lyle Cummins, 710.
⁸⁹ Lyle Cummins, 727.
⁹⁰ Lyle Cummins, 724.
⁹¹ John D. Alden (Article), 47.
⁹² Lyle Cummins, 356.
⁹³ Lyle Cummins, 700.
⁹⁴ James F. Calvert, 51.
⁹⁵ Lyle Cummins, 709.
⁹⁶ Lyle Cummins, 705-706.

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- ⁹⁷ Norman Friedman (*Through 1945*), 262.
⁹⁸ John D. Alden (Article), 48.
⁹⁹ John D. Alden (book), 92.
¹⁰⁰ John D. Alden (Article), 47.
¹⁰¹ John D. Alden (Article), 47.
¹⁰² James F. Calvert, 17.
¹⁰³ James F. Calvert, 40.
¹⁰⁴ James F. Calvert, 91, 97.
¹⁰⁵ James F. Calvert, 26.
¹⁰⁶ James F. Calvert, 101.
¹⁰⁷ James F. Calvert, 54.
¹⁰⁸ Clay Blair Jr., 418.
¹⁰⁹ Norman Friedman (*Through 1945*), 233.
¹¹⁰ James F. Calvert, 52.
¹¹¹ Norman Friedman (*Through 1945*), 236.
¹¹² Norman Friedman (*Through 1945*), 234.
¹¹³ Norman Friedman (*Through 1945*), 235.
¹¹⁴ Norman Friedman (*Through 1945*), 214.
¹¹⁵ Brayton Harris, 263.
¹¹⁶ Brayton Harris, 255.
¹¹⁷ Norman Friedman (*Through 1945*), 233.
¹¹⁸ John D. Alden (book), 92.
¹¹⁹ Edwin P. Hoyt, 186-187.
¹²⁰ Norman Friedman (*Through 1945*), 233, 352.
¹²¹ Norman Friedman (*Through 1945*), 352.
¹²² Edwin P. Hoyt, 1.
¹²³ Ronald H. Spector, *Eagle Against the Sun*. New York: The Free Press, 1985, 307.
¹²⁴ Edwin P. Hoyt, 255.
¹²⁵ Ronald H. Spector, 310.
¹²⁶ Edwin P. Hoyt, 265.

Appendix

	Cylinders	BHP	RPM	Bore × Stroke
NELSECO-Vickers (1911), E class	4	275	400	12.75 × 13.50
NELSECO-MAN (1913), K class: 75/6HS ^a	6	450	450	11.00 × 12.25
NELSECO (1918), M-1: 70/6 MS	5	420	350	10.50 × 16.00
NELSECO (1918), H, K re-engined: 240V8FS	8	240	350	9.00 × 12.50
McIntosh & Seymour, E-2 re-engined	8	250	375	9.00 × 13.00
NELSECO (1919), O and R classes: 6-EB-14	6	440	400	13.50 × 14.00
NELSECO (1919), S-1: 8-EB-15	8	600	380	13.50 × 15.00
Navy-NELSECO (1919), Navy S-3 class: 8-EB-16	8	700	350	14.50 × 16.00
NELSECO (1920), T class: 6-EB-19	8	1,000	375	18.00 × 19.00
Sulzer Bros. (1914), G-3	6	600	450	12.59 × 12.59
Busch-Sulzer (1916), Lake L class	6	600	375	12.50 × 14.50
Busch-Sulzer (1917), Lake N class	6	300	400	9.50 × 12.00
Busch-Sulzer (1918), Lake O and R classes	6	500	410	14.25 × 14.00
Busch-Sulzer (1919), S-2	6	900	350	14.87 × 16.37
Busch-Sulzer (1922), V-1 class ^a	6	2,250	310	21.63 × 21.63

^aIndicates 2-cycle engine.

Table 3: Early Submarine Diesel Engines.

Source: Cummins, Lyle. *Diesels for the First Stealth Weapon-Submarine Power 1902-1945*. Wilsonville, OR: Carnot Press, 2007.

Appendix

Table A-3. Lightweight Diesels

Type	Cylinders	Rating (BHP)	RPM	Bore x Stroke
MAN (<i>Cachalot</i>)	9	1,550	480	15.75 x 18.11
GM 16-258, <i>Cachalot</i> re-engined*	V-16	1,535	900	9.5 x 12.0
GM 12-258S, <i>Argonaut</i> re-engined*	V-12	1,500	900	9.5 x 12.0
GM 16-258, <i>Nautilus</i> re-engined*	V-16	2,000	900	9.5 x 12.0
Winton, prototype	V-12	950	720	8.0 x 10.0
Stearns, prototype	Diamond-4	321	1,300	5.25 x 8.5
Sun Ship, prototype	6	685	620	6.25 x 9.75
Continental, prototype	Radial-10	635	1,400	6.5 x 7.5
Electric Boat, prototype	V-16	635	1,150	7.0 x 8.25
Winton 201A <i>Porpoise</i> as built	V-16	1,300	750	8.0 x 10.0
GM 16-248 <i>Tamper</i> and later fleet boats	V-16	1,600	750	8.5 x 10.5
GM 16-278A, SS 313 and later fleet boats; <i>Narwhal</i> , SS 182-184, 188-190, 194, 253-264 re-engined; 1,200-BHP V-12 version in 172, 173, 175, re-engined	V-16	1,600	750	8.5 x 10.5
GM 16-338, 16-cylinder pancake in postwar submarines	Pancake	1,000	1,600	6.0 x 6.5
Fairbanks-Morse 38A8, <i>Plunger-Pollack</i>	8	1,300	720	8.0 x 10.0
Fairbanks-Morse 38D8-4, 179-180 re-engined, SS 201, and later	9	1,600	720	8.5 x 10.0
Fairbanks-Morse 38A6-4, postwar lightweight version of Fairbanks-Morse engine	8	1,000	1,335	6.75 x 8.0
HOR-MAN, <i>Pompano</i>	8	1,300	700	9.056 x 13.38
Electric Boat, 1933 engine for S-20: 16VM1		635	1,175	6.25 x 8.25
Electric Boat, <i>Mackerel</i> : 65MIR145*	6	850	460	14.0 x 14.5
ALCO, <i>Marlin</i> *	6	900	900	12.5 x 13.0

Table 4: High Speed Light Weight Diesels.

Source: Cummins, Lyle. *Diesels for the First Stealth Weapon-Submarine Power 1902-1945*. Wilsonville, OR: Carnot Press, 2007.

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